



Jet Propulsion Laboratory
California Institute of Technology



Exoplanet Exploration Program

Exoplanet Exploration Program Technology Update

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Exoplanet Exploration Program

Jet Propulsion Laboratory / California Institute of Technology

ExoPAG 20, Bellevue, WA

23 June 2019

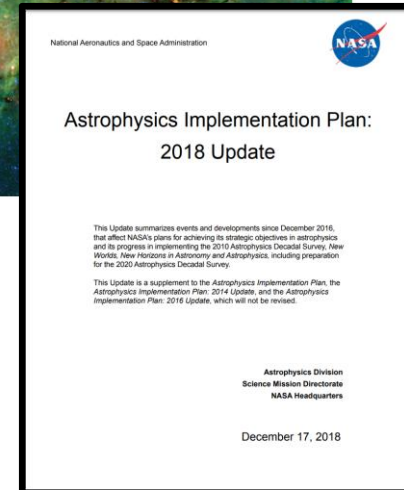
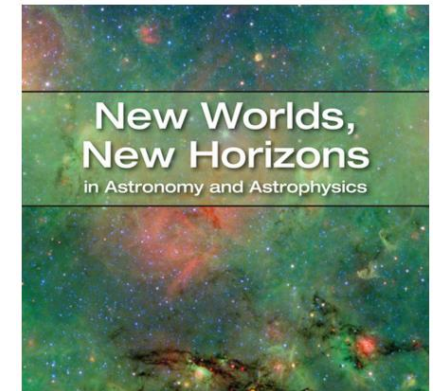
2010 Decadal Survey Recommendations

... and NASA's response



Exoplanet Exploration Program

Decadal Survey Recommendation	NASA Actions
Large-scale 1. WFIRST	In Phase A, launch in mid-2020s (see Section 4)
Large-Scale 2. Augmentation to Explorer Program	Executing 4 Announcements of Opportunity (AOs) per decade (see Section 5)
Large-Scale 3. LISA	Partnering on ESA's space-based gravitational wave observatory (see Section 6.1)
Large-Scale 4. IXO	Partnering on ESA's Athena X-ray observatory (see Section 6.2)
Medium-Scale 1. New Worlds Technology Development Program	WFIRST coronagraph; starshade and coronagraph technology development; Doppler spectrograph on WIYN telescope; exozodiacal dust survey with LBTI (see Section 7.1)
Medium-Scale 2. Inflation Probe Technology Development Program	Multiple balloon-borne investigations plus SAT investments (see Section 7.2)
Small-Scale. Research Program Augmentations	R&A as of FY2016 up 20% from FY2010; increase not targeted except TCAN (see Section 7.3)
Small-Scale. Intermediate Technology Development Augmentation	Initiated Strategic Astrophysics Technology program; focused on identified strategic missions
Small-Scale. SPICA (U.S. contribution)	Not supported as a strategic contribution; candidate for Explorer Mission of Opportunity



APD Implementation Plan (2012, 2014, 2016, 2018)

Table 1. Recommended space activities of the 2010 Decadal Survey supported by the FY 2016 NASA Appropriation, the FY 2017 President's Budget Request, and its notional out year planning budget.

2010 Decadal Survey Recommendation

Medium Scale Category



Exoplanet Exploration Program

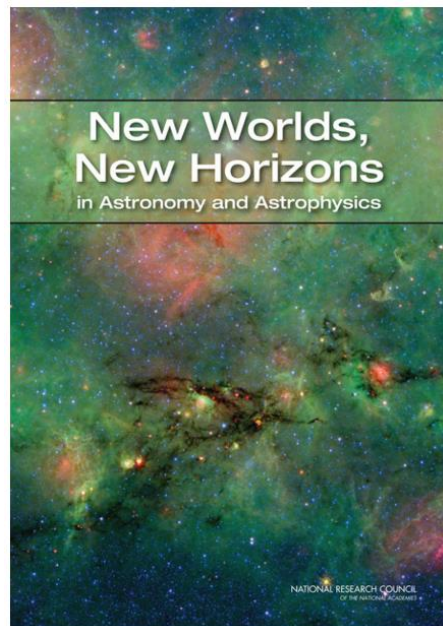


TABLE ES.4 Space: Recommended Activities—Medium-Scale (Priority Order)

Recommendation	Science	Appraisal of Costs ^a
1. New Worlds Technology Development Program	Preparation for a planet-imaging mission beyond 2020, including precursor science activities	\$100M to \$200M
2. Inflation Probe Technology Development Program	Cosmic microwave background (CMB)/inflation technology development and preparation for a possible mission beyond 2020	\$60M to \$200M

*“...high-priority science areas for which mid-term investments are needed beginning early in the decade, including development of a variety of technologies for exoplanet imaging, such as **coronagraphs, interferometers, and starshades**, leading to possible late-decade down-selecting.”*

Exoplanet Science Strategy Report

Released September 5, 2018 by the National Academies



Exoplanet Exploration Program

Recommendation #1:

NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars.



Recommendation #3:

NASA and NSF should establish a strategic initiative in extremely precise radial velocities (EPRVs) to develop methods and facilities for measuring the masses of temperate terrestrial planets orbiting Sun-like stars.

TECHNOLOGY

Angular Resolution: Interferometry

Angular Resolution and Collecting Area: Large Space Telescopes

Contrast Stability: Ultrastable Structures

Detection Sensitivity: Advanced Detectors

Starlight Suppression: Starshades

Starlight Suppression: Coronagraphs

MISSIONS



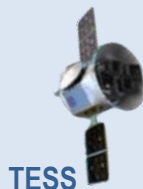
Hubble



Spitzer



Kepler



TESS



JWST



WFIRST



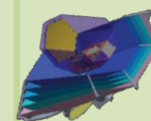
Starshade
Rendezvous



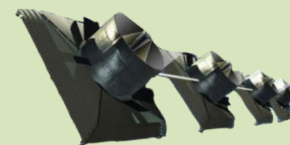
LUVOIR



HabEx



Origins



Exo-Earth
Interferometer

TODAY

2020s

2025s

2030s

2035 and beyond

SCIENCE

Exoplanetary
Atmospheres
Hot Jupiters

Exoplanet
Abundance

Nearest Transiting
Planets

Atmospheric
Chemistry

Direct Imaging
Exozodiacal Dust
Exoplanet Diversity

Habitable
Exo-Earth
Discovery

M-Dwarf Rocky Planet
Biosignatures
Cool Gas Giants

Exo-Earth
Biosignatures
Habitable
Exo-Earth
Abundance

Life
Verification

Possible Pending Decadal Survey

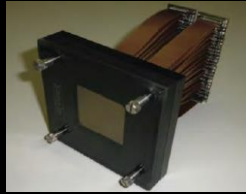
Coronagraphy (and Telescopes)

V/NIR Coronagraph/Telescope Technology Gaps

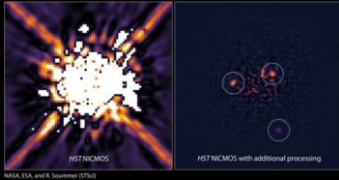
Contrast



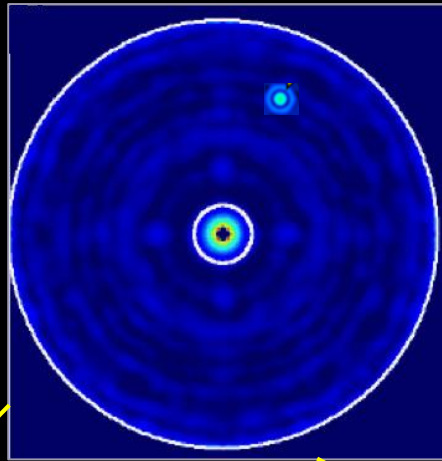
CG-2: Coronagraph Architecture



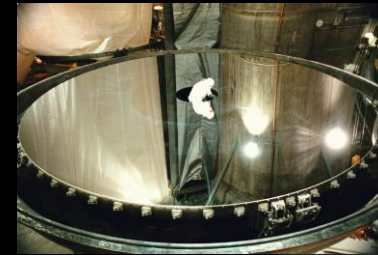
CG-3: Deformable Mirrors



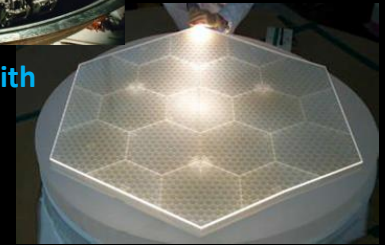
CG-4: Data Post-Processing



Angular Resolution

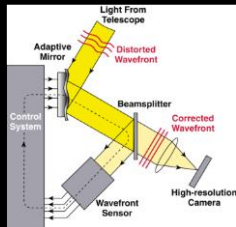


CG-1: Large Monolith Mirrors



CG-1: Segmented Mirrors

Contrast Stability



CG-5: Wavefront Sensing and Control

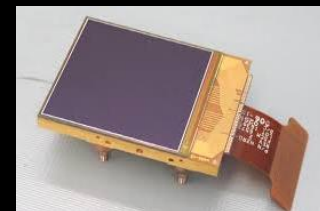
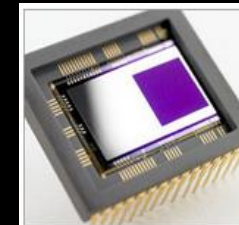


CG-6: Mirror Segment Phasing



CG-7: Telescope Vibration Sensing and Control or Reduction

Detection Sensitivity



Ultra-low Noise Visible (CG-8) and Infrared (CG-9) Detectors

Strategic Astrophysics Technology (SAT)

Competitive grant program



Exoplanet Exploration Program

- **SAT-17 Rémi Soummer (STScI)**
Milestone Whitepaper approved
- **SAT-17 Olivier Guyon (UA)**
Milestone Whitepaper 1 approved
- **SAT-17 Gene Serabyn (NASA/JPL)**
Milestone Whitepaper under review
- **SAT-17 Bernie Rauscher (NASA/GSFC)**
Milestone Whitepaper under review



*First System-level
Demonstration of
High-Contrast for
Future Segmented
Space Telescopes*



*Linear Wavefront Control
for High Contrast Imaging*



*Vortex Coronagraph
High Contrast
Demonstrations*



*Radiation Tolerant,
Photon Counting,
Visible and Near-IR Detectors
For Space Coronagraphs
and Starshades*

<https://exoplanets.nasa.gov/exep/technology/TDEM-awards/>

ExEP's Decadal Survey Testbed



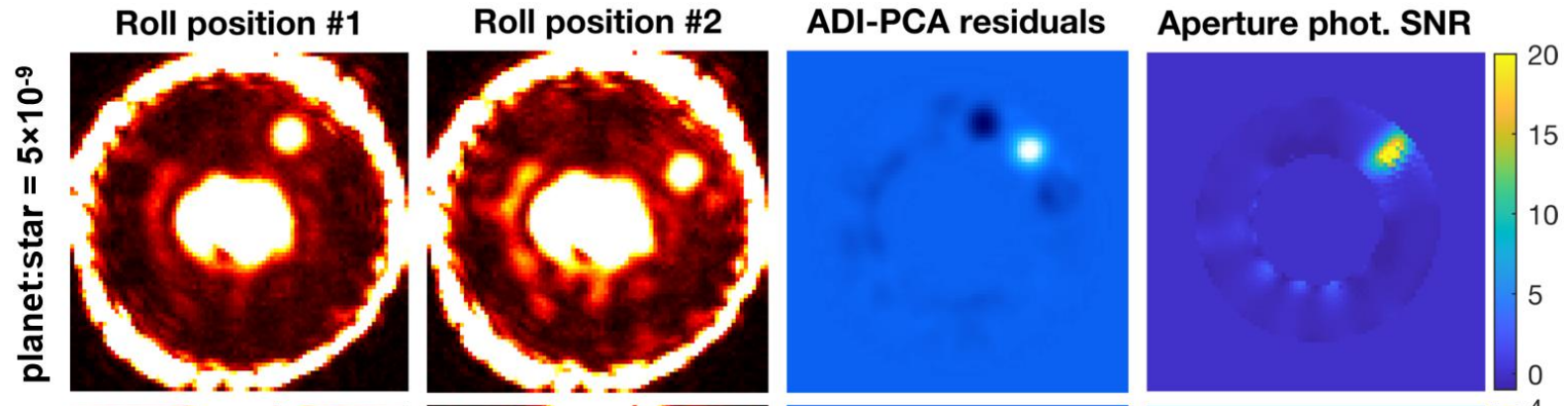
Exoplanet Exploration Program



ExEP's Decadal Survey Testbed



Exoplanet Exploration Program



The DST established a new record 3.8×10^{-10} contrast using a classic Lyot coronagraph mask.

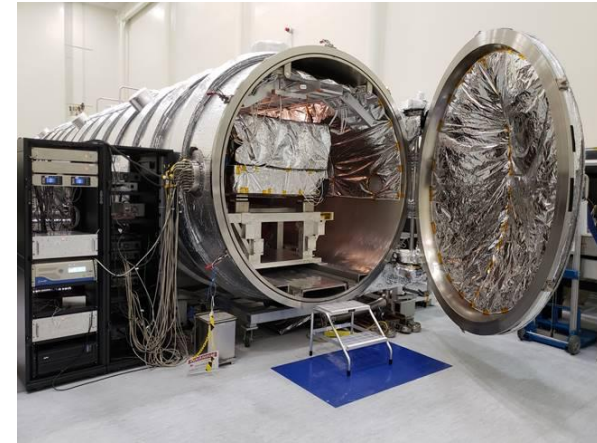
- It was achieved at 550 nm and 10% bandpass over 3-8 λ/D .
- Analysis indicates the testbed and vacuum facility contribute about 2×10^{-10} contrast, very close to the 1×10^{-10} goal

ExEP's Decadal Survey Testbed

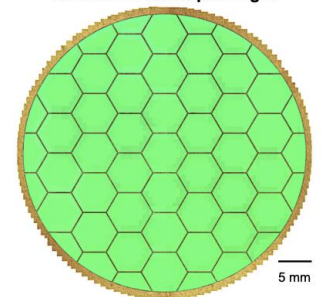


Exoplanet Exploration Program

- The commissioning phase of the DST is now over and the facility can be handed over to the SAT PI's.
- WFIRST CGI currently using the DST demonstrating the performance capabilities with a second source of deformable mirrors (MEMS)
- Phase 2 of commissioning: free-standing pupil mask with a segmented pattern, repeat demo
- Phase 3: add a High-Order Wavefront Sensor (HOWFS) and simulated dynamic wavefront errors from segment-segment piston/tip/tilt



Stitched microscope images

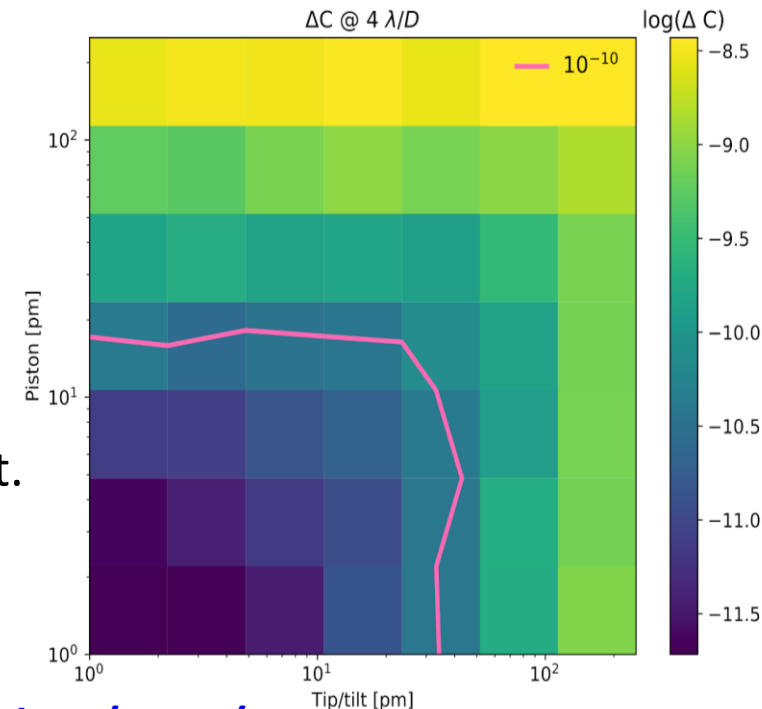


ExEP's Segmented Coronagraph Design and Analysis Study



Exoplanet Exploration Program

- ExEP-chartered activity to investigate coronagraph designs for future segmented/obscured space telescopes
 - Multiple coronagraph architectures meet contrast performance
 - Robustness to expected non-idealities now under investigation:
 - Finite stellar diameter
 - Low-order wavefront errors
 - Segment/segment errors
 - APLC, Vortex, and PIAA designs are promising
- Example: APLC for LUVOIR-A requires 10-20 pm piston segment/segment piston and tip/tilt alignment to maintain better than 10^{-10} contrast.



Systems-Level Segmented Telescope Design Studies



Exoplanet Exploration Program

- Final reports from Phase I system-level studies available including technology gap lists <https://astrostrategictech.us>



Ultra-Stable Large Telescope Research and Analysis (ULTRA),
PI **Scott Knight** (Ball Aerospace)



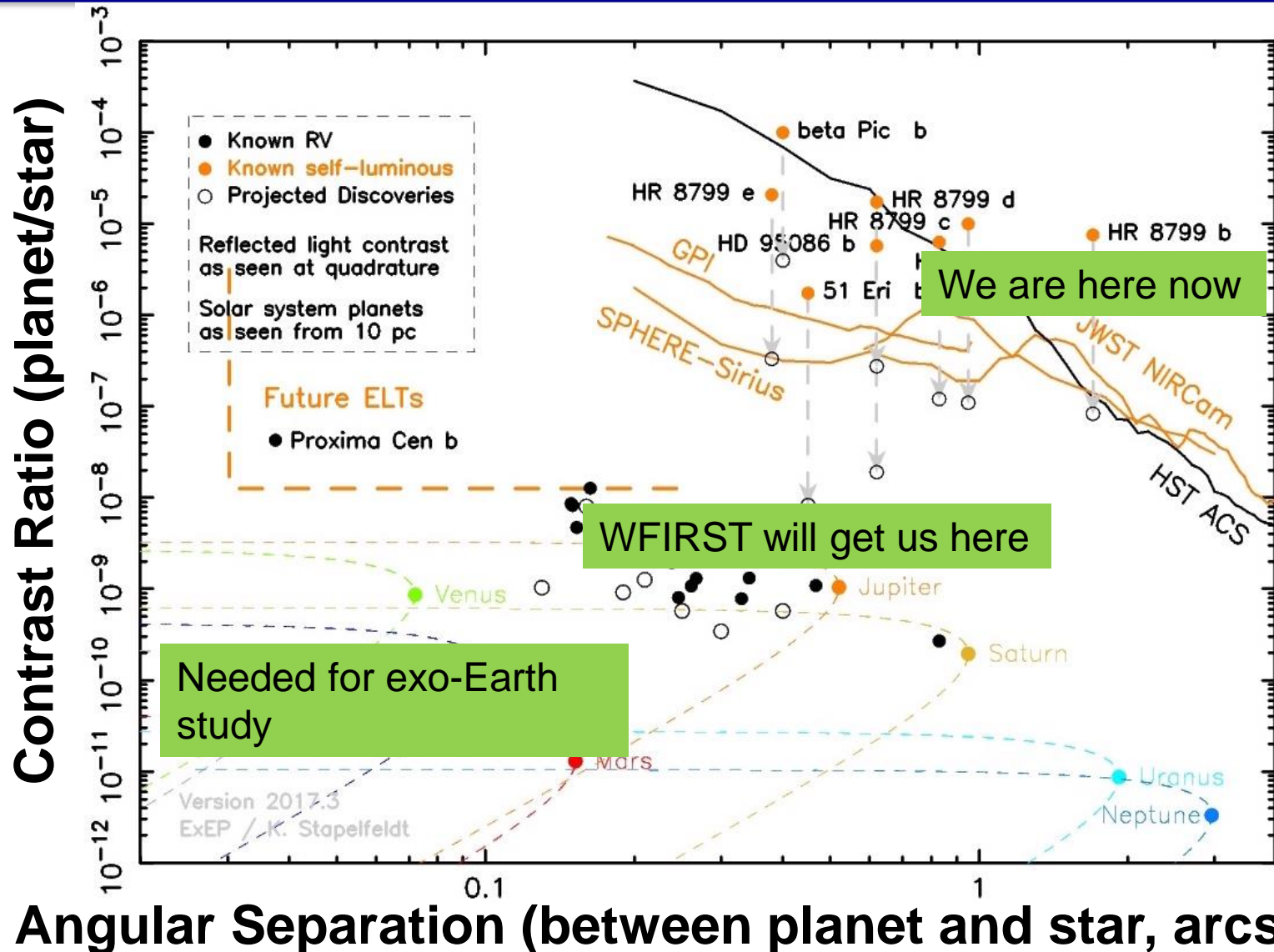
System-Level Segmented Telescope Design
PI **Larry Dewell** (Lockheed Martin)

- See Technology Colloquium Series for summary talks:
https://exoplanets.nasa.gov/exep/technology/tech_colloquium/
- Phase II (in selection phase) will aim to mature key technologies identified in Phase I

Still a Way to go to Imaging Exo-Earths



Exoplanet Exploration Program



WFIRST Coronagraph

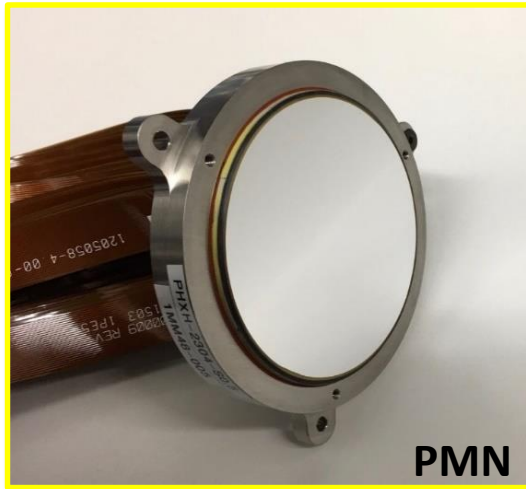
Technology Development Continues



Exoplanet Exploration Program

- Instrument PDR in Sept
- Several technology trade studies wrapping up

Deformable Mirrors



PMN

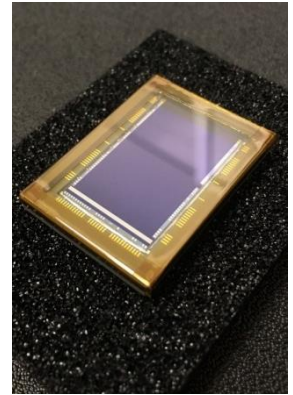


MEMS

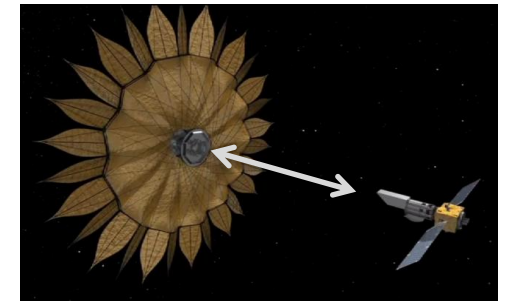
- Contrast performance and stability tests with MEMS in vacuum chamber
- Wire connector modifications on PMN

EMCCD

Radiation hardness has improved ~ 1.5 times (based on charge transfer efficiency and cosmic ray impacts)



Compatibility with Starshade



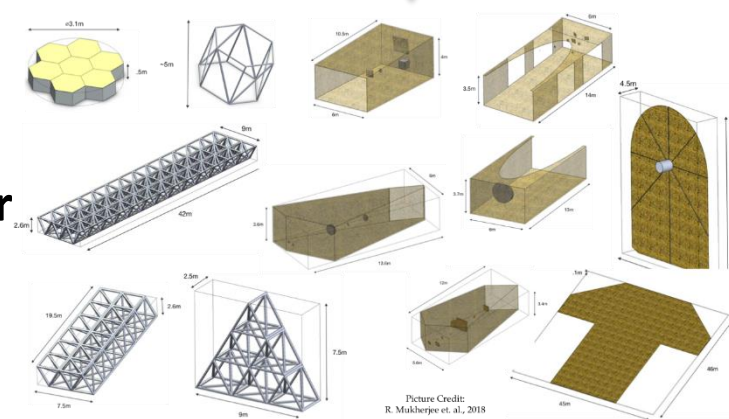
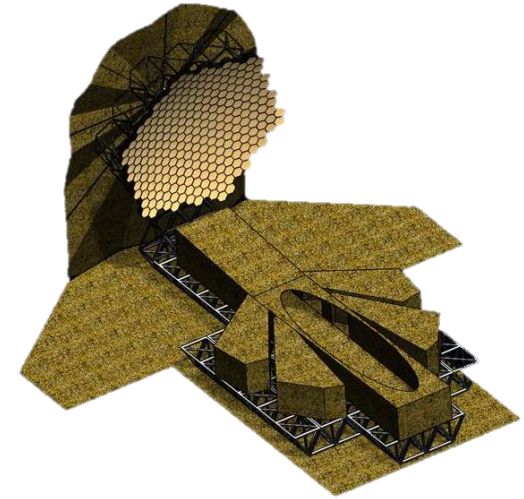
Using LOWFS as a pupil plane formation sensor

In-Space Assembled Telescope Study



Exoplanet Exploration Program

- NASA-chartered study to answer the question:
When is it advantageous assembling space telescopes in space rather than building them on Earth and deploying them autonomously from individual launch vehicles?
- Final deliverable is a Whitepaper to the Decadal Survey Committee in 2019
- No “tyranny of the launch vehicle”
- Eliminates complex autonomous self-deployments
- Mitigates the risks associated with a single LV or deployment anomaly
- Relaxes mass and volume constraints
- Eliminates costly systems-level testing activities



Picture Credit:
R. Mukherjee et al., 2018

Servicing Dilemma Solved

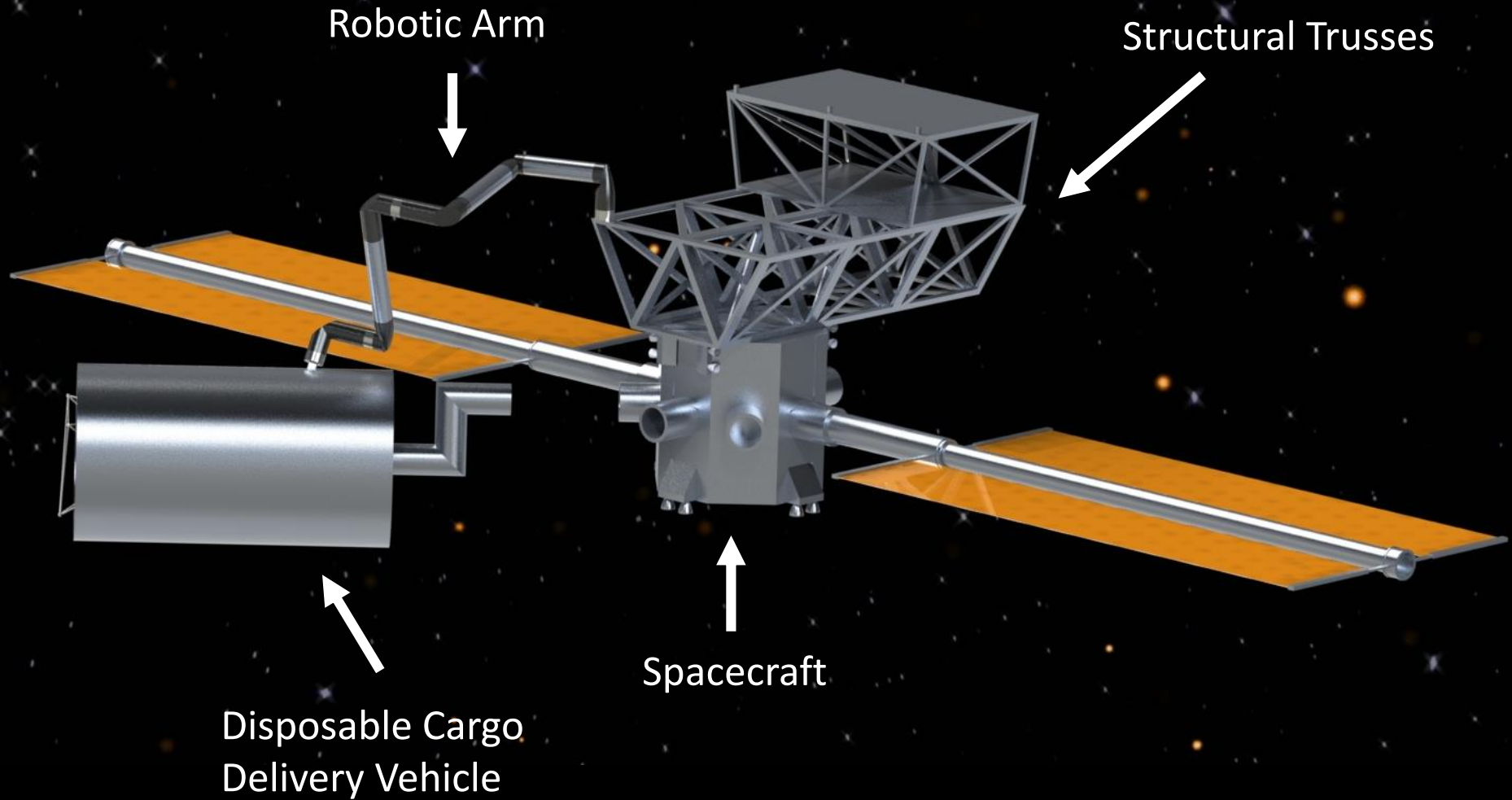


Illustration from R. Mukherjee and D. Mick (NASA/JPL/Caltech)

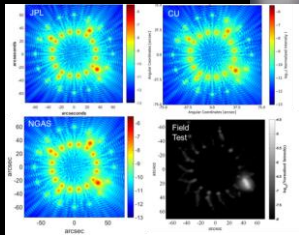
Starshade

Starshade Technology Gaps

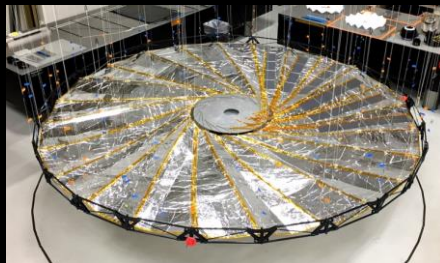
Contrast



S-1: Controlling Scattered Sunlight



S-2: Starlight Suppression and Model Validation

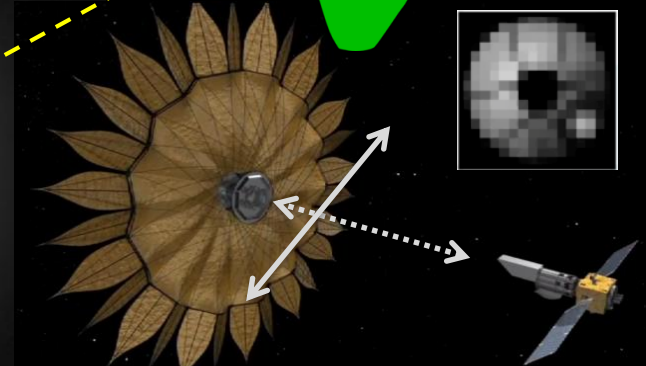


S-5: Petal Positioning Accuracy and Opaque Structure

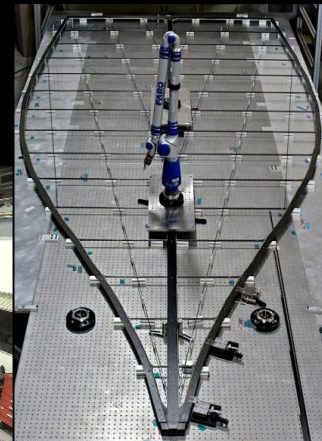
Deployment Accuracy and Shape Stability



Formation Sensing



S-3: Lateral Formation Sensing



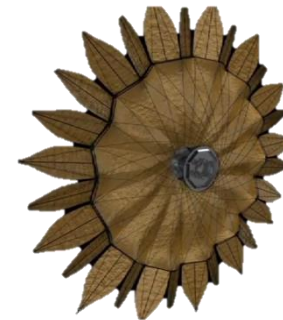
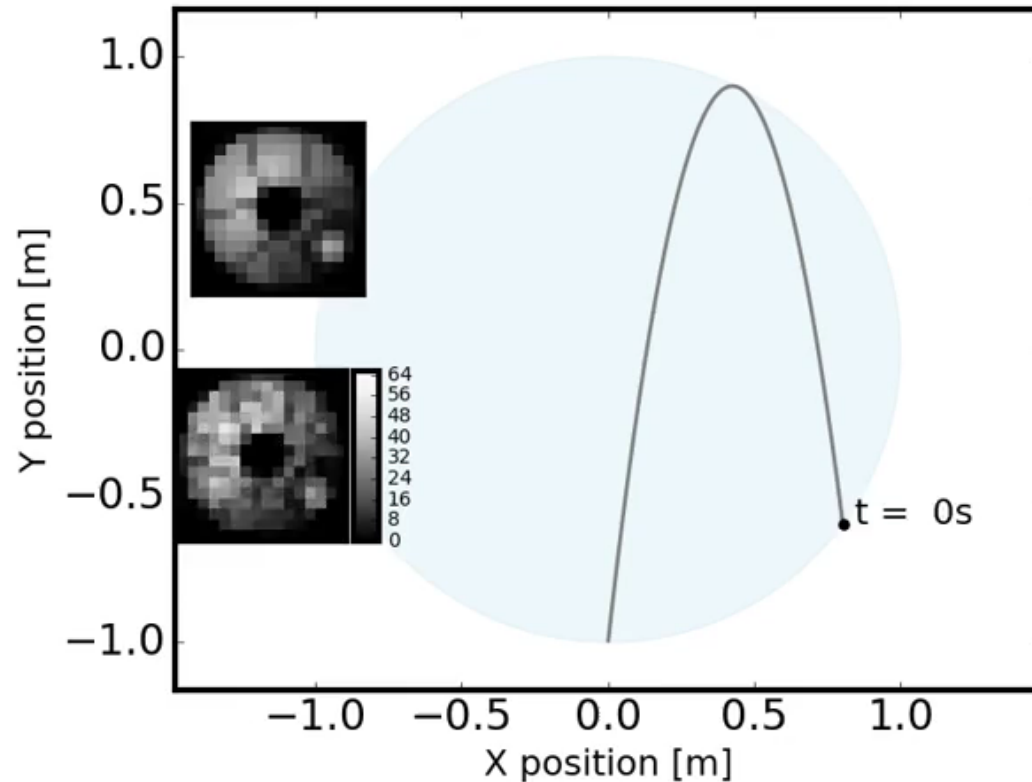
S-4: Petal Shape And Stability

Starshade Technology Development

Formation Sensing and Control



Exoplanet Exploration Program



- Lab demonstration when scaled meets lateral off-set requirement
- Successful Milestone Review in January 2019
- Technology Gap closed

<https://exoplanets.nasa.gov/exep/technology/starshade/>

Starshade Technology Development

Starlight Suppression and Model Validation

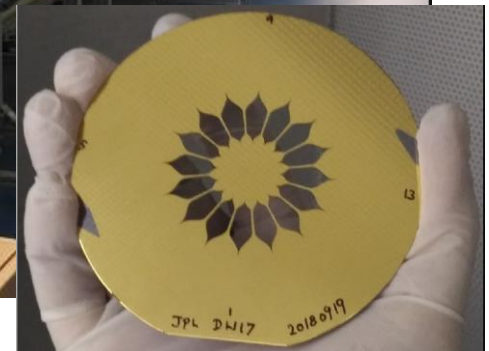


Exoplanet Exploration Program



Frick Testbed, Princeton University

Lead: Anthony Harness



<https://exoplanets.nasa.gov/exep/technology/starshade/>

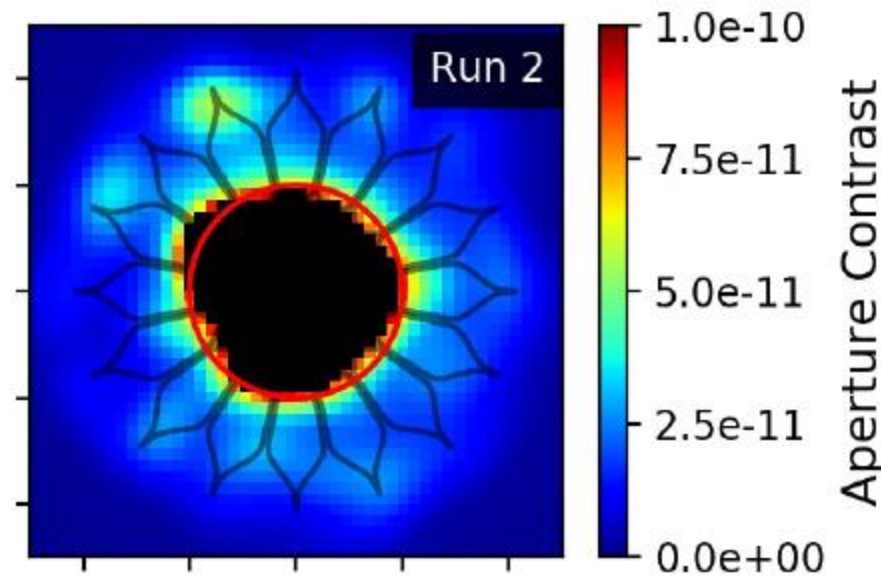
Starshade Technology Development

Starlight Suppression and Model Validation



Exoplanet Exploration Program

Black pixels
exceed 10^{-10}



- Averaged narrowband demonstration met $< 10^{-10}$ contrast goal at the inner working angle
- Vector diffraction effect identified; predicted to go away at larger scales.
- Successful milestone review in April

<https://exoplanets.nasa.gov/exep/technology/starshade/>

Interferometry

Interferometry



Exoplanet Exploration Program

- **Next decade?**
- **Watch for recommendations from Astro2020**

Extreme Precision Radial Velocity



- **Planning the steps forward...**
- **See Eric Mamajek's talk for details.**

Looking Ahead 6 Months



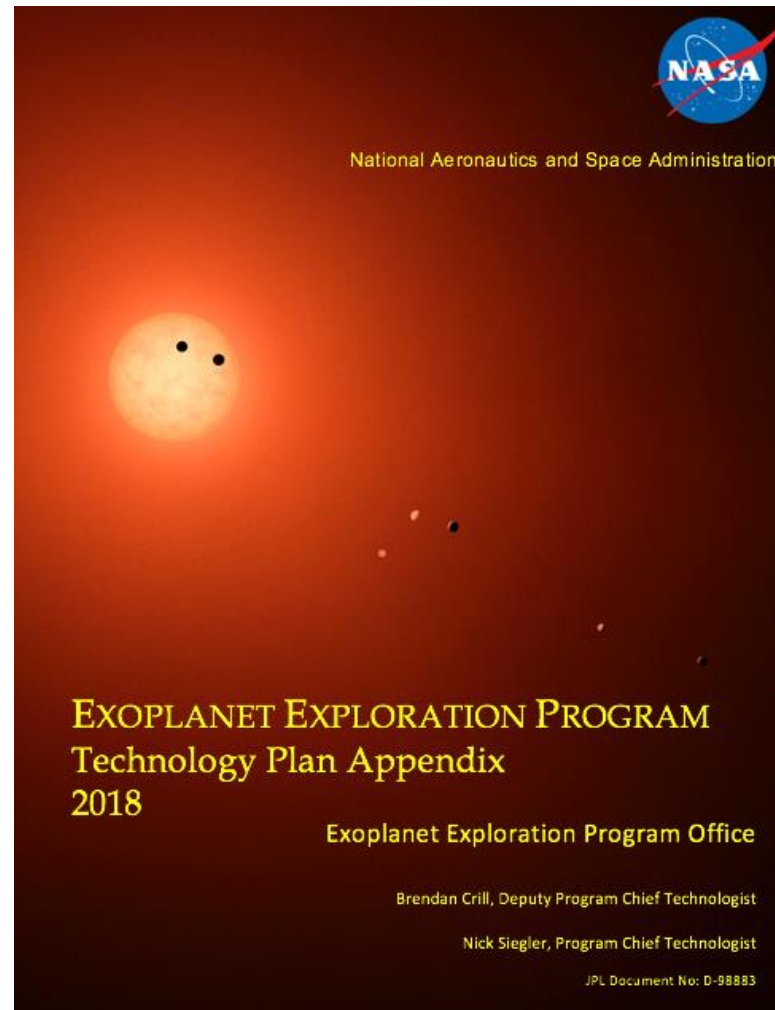
Exoplanet Exploration Program

- **Technology Readiness Level and Roadmap Assessment of the four Large Mission STDTs in behalf of NASA's Astrophysics Division**
- **Updated prioritized Astrophysics Technology Gap List (end Summer 2019)**
- **SAT**
 - Coronagraph demos scheduled for HCIT: Vortex (Serabyn), PIAACMC (Belikov), Hybrid Lyot (Trauger)
 - Final Reports on 1. Polarization (Breckinridge), 2. MEMS DMs (Bierden)
- **APC Whitepaper to Astro2020**
 - SCDA reports: whitepaper, further publications
 - Overall exoplanets technology whitepaper, iSAT whitepaper
- **Decadal Survey Testbed**
 - MEMS deformable mirrors tests
 - First vacuum demonstration of a coronagraph with a segmented pupil

Visit the ExEP website for more details



Exoplanet Exploration Program



<https://exoplanets.nasa.gov/exep/>